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METEOROLOGICAL RESEARCH COMMITTEE

Investigation of high altitude clear air turbulence near jet streams: special flights by R.A.F. and R.A.E. aircraft

by

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Summary

Special investigational flights were made by Royal Air Force and R.A.E. jet aircraft to explore and report the variations in the occurrence and severity of clear air turbulence in different parts of jet streams over the British Isles. Apart from a few exceptions it was found that moderate or severe turbulence occurred mainly on the low pressure side of the axis and to a lesser extent on the high pressure side above the axis; very few incidents were reported on the high pressure side below the axis. It was tentatively deduced that there was an approximately equal probability that the worst bumpiness encountered near a jet stream was either severe, moderate or perceptible, and that a small proportion of jet streams were not turbulent at all. Generally severe turbulence occurred when the vector difference between the wind at 300 and 500 mb. levels at the jet exceeded 35 knots and the horizontal shear on the low pressure side at the level of the axis of the jet exceeded 0.2 $hr.^{-1}$

1. Introduction. There is a considerable amount of statistical information now available concerning the frequency, vertical and horizontal extent, strength and levels of occurrence of turbulence over the British Isles and Western Europe at heights between 15,000 and 40,000 ft. (1, 2). High altitude clear air turbulence has been observed in almost all weather situations, though it appears that there are two factors, one or other or both of which are usually associated with its occurrence, namely, strong shear of wind in the vertical and strong shear of wind in the horizontal or isentropic surfaces.

A recent analysis of reports of severe turbulence encountered by aircraft over the United Kingdom (3) showed that nearly 70 per cent of the incidents occurred in association with well defined jet streams. The others were associated with upper lows, upper troughs, discontinuous tropopause surfaces or strong winds not associated with jet streams but a small number had no obvious association with any configuration in the upper air pattern. 75% of those associated with jet streams were on the low pressure side of the stream.

2. Special flights by R.A.F. aircraft. In order to confirm or correct certain aspects of the above results, and to study further the occurrence of turbulence near jet streams it was agreed that at certain airfields the Royal Air Force would make investigational flights in areas specified by the Meteorological Office. The investigations were made by the dispatch of a special aircraft, or by diverting an aircraft already airborne and, at times, it was made in conjunction with the normal daily flying programme of the station.

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But the amount of flying effort available was subject to the proviso that operational and training commitments took first priority, which was often most unfortunate from the point of view of the investigation because many opportunities of flying and investigating turbulence in interesting weather situations were unavoidably missed.

This investigation was given the code name "Upper Bumps" and was started in March 1952. Reports obtained during the period up to February 1953 have been studied and are dealt with in this paper.

The main interest was the jet stream with which turbulence at high levels is now known to be mostly associated. The Meteorological Officer at each of the airfields nominated to take part in the investigation informed the Wing Commander Flying when the conditions appeared favourable for the occurrence of turbulence, giving as much advance notification as possible. A request for an investigational flight was then made and the approximate area or route, and the height of flight specified.

The pilot undertaking the flight was asked to note the occurrence of turbulence throughout the flight, observations from height above 20,000 feet being the main interest. Nil reports were regarded as being just as important as positive reports. Details were required of the severity of the turbulence, that is, whether it could be classed as, perceptible, moderate or severe.

The aircraft used were not fitted with any special instruments and therefore the reports made by the pilots could only be qualitative assessments. In order to achieve as much consistency as possible with regard to the severity of the turbulence encountered, all pilots were asked to pay careful attention to a scale which has been described in reference (4).

Pilots carrying out these investigational flights were encouraged to report special or unusual features of the turbulence and to state if any action was taken either by climbing or descending or altering course or speed, to fly out of turbulent areas. The boundaries of the turbulent zones were discovered and noted wherever possible. No attempt was made to carry out a systematic investigation of the variations along the jet streams; only the cross sections of the jets were explored.

At the conclusion of each investigational flight the pilot was "debriefed" by the Meteorological Officer on the station and a special form was completed. An example of a completed form is given in Appendix I.

In all 23 jet streams occurring over the British Isles were investigated during the first year that Operation "Upper Bumps" was carried out. The number of flights made either across or in particular regions of jet streams varied from one to twelve per jet, the average being about three. It was not possible for the whole cross section of a jet stream to be thoroughly investigated in each case.

3. Analysis of results. The track of each flight was plotted on a graph showing the position of the flight relative to the jet stream. The method adopted was similar to that in reference (3), except that mean isopleths of wind speed have not been inserted. Vertical units are the difference between the pressure at the axis of the jet and the pressure on the I.C.A.N. scale corresponding to the height of the aircraft. The horizontal unit is the distance from the jet centre to the point at the same level on the low pressure side of the jet at which the wind speed decreased to half its maximum value. Figs. 1 and 2 show diagrammatically all flights carried out during the periods March to August 1952 and September 1952 to February 1953 respectively.

An attempt was made to classify each jet according to vertical and horizontal shear and to ascertain if there was any correlation between these two parameters and the intensity of the turbulence experienced. The vertical shear was taken as the shear between the 300 and 500 mb. levels at the axis of the jet, these levels being chosen because they are standard levels used for constructing

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contour charts. This method of evaluating the vertical shear suffers from a serious disadvantage in that it does not give a representative value when the axis of the jet lies about halfway between the two levels but such cases were quite few.

The horizontal shear was estimated on the low pressure side of the jet and at the same level as the axis of the jet. The value obtained refers to the average shear over the distance over which the wind falls to half its maximum value at the axis of the jet. In practically all cases the radius of curvature of the stream lines was so large that no adjustment was considered necessary for it.

In order to ascertain whether a relationship existed between the shear (both vertical and horizontal) and the severity of the bumpiness Figs. 3-7 were constructed. Fig. 3 shows diagrammatically the most severe intensity of turbulence encountered near each of the jet streams investigated plotted for the appropriate values of the horizontal and vertical shear. Similarly Figs. 4-7 show the most severe turbulence experienced in the four quadrants of the jet stream.

The various reports of turbulence experienced during the flights were also examined in relation to the position of occurrence along the jet stream, that is, whether they occurred near the entrance, middle or exit. The result is given in the table below:-

Table I

	Nil	Perceptible	Moderate	Severe
Entrance	0	5	0	0
Middle	24	24	21	11
Exit	0	10	12	2

It would appear from these figures that the turbulence was more severe near the exit than the entrance to the jets but this difference may not be significant because the number of cases was rather small and there were more flights made near exits than entrances to jets.

4. R.A.E. Turbulence Search Flights. During the period April to December 1951 the Aero. Flight of the Royal Aircraft Establishment, South Farnborough carried out some investigational flights on the same lines as the Royal Air Force "Upper Bumps" flights. Seven such flights to investigate turbulence near jet streams have been analysed by the same method and the results of the analysis are displayed in Figs. 8 and 9. A study of the most severe turbulence experienced in the four quadrants of the jet stream did not reveal anything of interest, mainly because the number of flights was small. None of the flights was made near the entrance or exit of the jet so it was not possible to learn anything from this series regarding the relative severity of turbulence in these two regions.

5. Summary and conclusions. 23 jet streams were investigated by the Royal Air Force and seven by the R.A.E. Aero. Flight. The worst turbulence encountered near any of the jets is shown in the following table:

Table II

	R.A.F. Flights	R.A.E. Flights	Totals
Severe turbulence	9	0	9
Moderate turbulence	9	1	10
Perceptible turbulence	3	6	9
No turbulence	2	0	2
	23	7	30

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When examining the above table it must be realised that on account of various operational reasons, such as shortage of aircraft etc., the amount of flying carried out varied considerably with different jet streams. Moreover, in some of them the investigational flights may not have been made in the most turbulent part of the jet. There is no doubt that further work needs to be done before a true and comprehensive picture can be obtained but the following tentative conclusions can be put forward.

(a) All jet streams are not turbulent although the great majority of them are.

(b) When an aircraft is flying near a jet stream there is approximately an equal probability that the worst bumpiness encountered will be either severe, moderate or perceptible in intensity.

No decisive result was obtained from the study of the variation in the severity of the bumpiness with the horizontal and vertical shear in the vicinity of the jet stream (Figs. 3-7 and 9). But in general it appears that severe turbulence occurred when the vector difference between the wind at the 300 and 500 mb. level was 35 kt. or more and the horizontal shear was 0.2 $hr.^{-1}$ or more.

The analysis of all the investigational flights in relation to their position with respect to the axis of the jet, shown diagrammatically in Figs. 1, 2 and 8 confirms previous findings on the subject. With only a few exceptions the moderate and severe incidents occurred on the low pressure side of the jet and on the high pressure side above the axis; there were very few on the high pressure side below the axis.

An examination of the variation along the axis of the jet did not produce any really conclusive results.

References

1. Hislop, G.S. — Clear Air Turbulence over Europe. J.R. Aero. Soc. 55, 1951, p. 185.

2. Bannon, J.K. — Meteorological aspects of turbulence affecting aircraft at high altitude. Prof. Notes, 7, No. 104, 1951. Meteorological Office, London.

3. Bannon, J.K. — Weather systems associated with some occasions of severe turbulence at high altitude. Met. Mag., London, 81, 1952, p. 97.

4. Jones, D.C.E. — Weather systems associated with some occasions of severe turbulence in clear air at high altitude - a further analysis. M.R.P. 828.

APPENDIX I

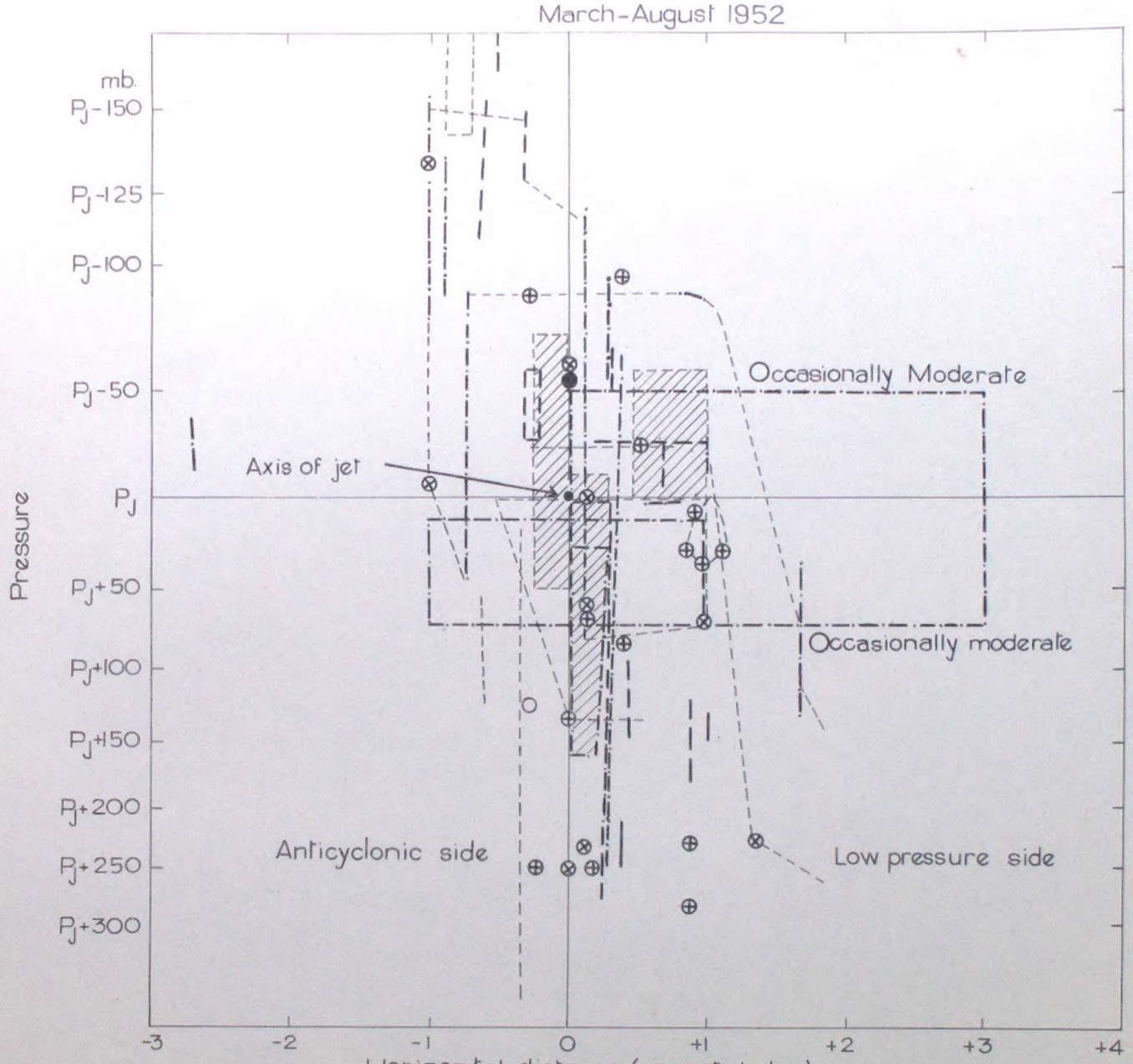
REPORT OF OCCURRENCE OF CLEAR AIR TURBULENCE

1. Aircraft type and number — Canberra W.D. 986
2. Unit and Station — 617 Squadron Royal Air Force Binbrook
3. Captain and Crew — Fg.Off.Dowling Crew:- Fg.Offs.Johnson and White.
4. Date/time group in respect and incident 241235 - 241420z 24th April, 1952.
5. Position of start of turbulence See 11.
6. Instrument readings as at position given in 5 above:-
   (i) Altimeter Sub-scale setting 1019 mb.
   (ii) Indicated Airspeed
   (iii) Magnetic Heading
   (iv) Indicated Air Temperature
7. Magnitude of turbulence — See 11. below
8. Extent and depth of turbulent region
9. Weather conditions in locality of incident
10. Other information
11. Remarks. Upper Bumps. Special flight to investigate jet stream extending from the Western Isles to Wales to Brittany. Aircraft sent on route Binbrook - Castle Archdale - Binbrook.

Time (GMT)	Position (Lat° Long°)	Turbulence Commenced (Height in ft.)	Turbulence Finished (Height in ft.)	I.A.S. (Kt.)	Heading (°Mag.)	Indicated Temperature (°C)
1242	53.25N 01.10W	Slight. 21,000	25,000	300	299	-
1247	53.35N 02.10W	Slight. 35,000 for 6 mins.		250	299	-27
1255	53.47N 03.20W	Slight. 32,500	35,000 (None above 35,000)	230	299	-28/-27
1306	53.55N 05.12W	Slight. 35,000	31,000 (Increased slightly at 33,000. Very slight to 24,000)	230	310	-34
1313	54.09N 06.00W	Slight. 25,000	34,500	230	310	-31 at 34,000
1315	54.12N 06.15W	Moderate 29,000 (moderate at this level only.)				
1326	54.30N 07.25W	Slight. 34,500	41,500 (Moderate at 39,000 only)	230	108	-30
1336	54.21N 05.27W	Mod. bec. Slight	39,000 41,500	230	115	-31
1343	54.03N 04.15W	Slight 38,000	23,000 (Moderate at 24,000 only)	230	110	-
1352	53.30N 02.12W	Moderate 24,000	- (Extended at this level to 53.29N 01.59W.)	230	110	-24
1355	53.25N 01.24W	Slight 29,500	31,000	230	110	-23
1359) 1402)	Descent at Binbrook	Moderate 16,000	-	230	075	-

Weather over route — Generally cloudy with cloud tops at 9,500 feet. Beyond 5deg. W. Rolls of Cirrus at 31,000/34,000 feet. Around 7deg. W. Rolls of Ac/As at 27,500 feet.

Fig. 1
Positions relative to the axis of jet streams of flights made by the R.A.F.
14 jet streams
March-August 1952



O or ___ Nil turbulence ⊕ or _._._ Perceptible turbulence ⊗ or _ _ Moderate turbulence
● or _ Severe turbulence ▨ Zone of turbulence

P_J is the pressure at the axis of the jet

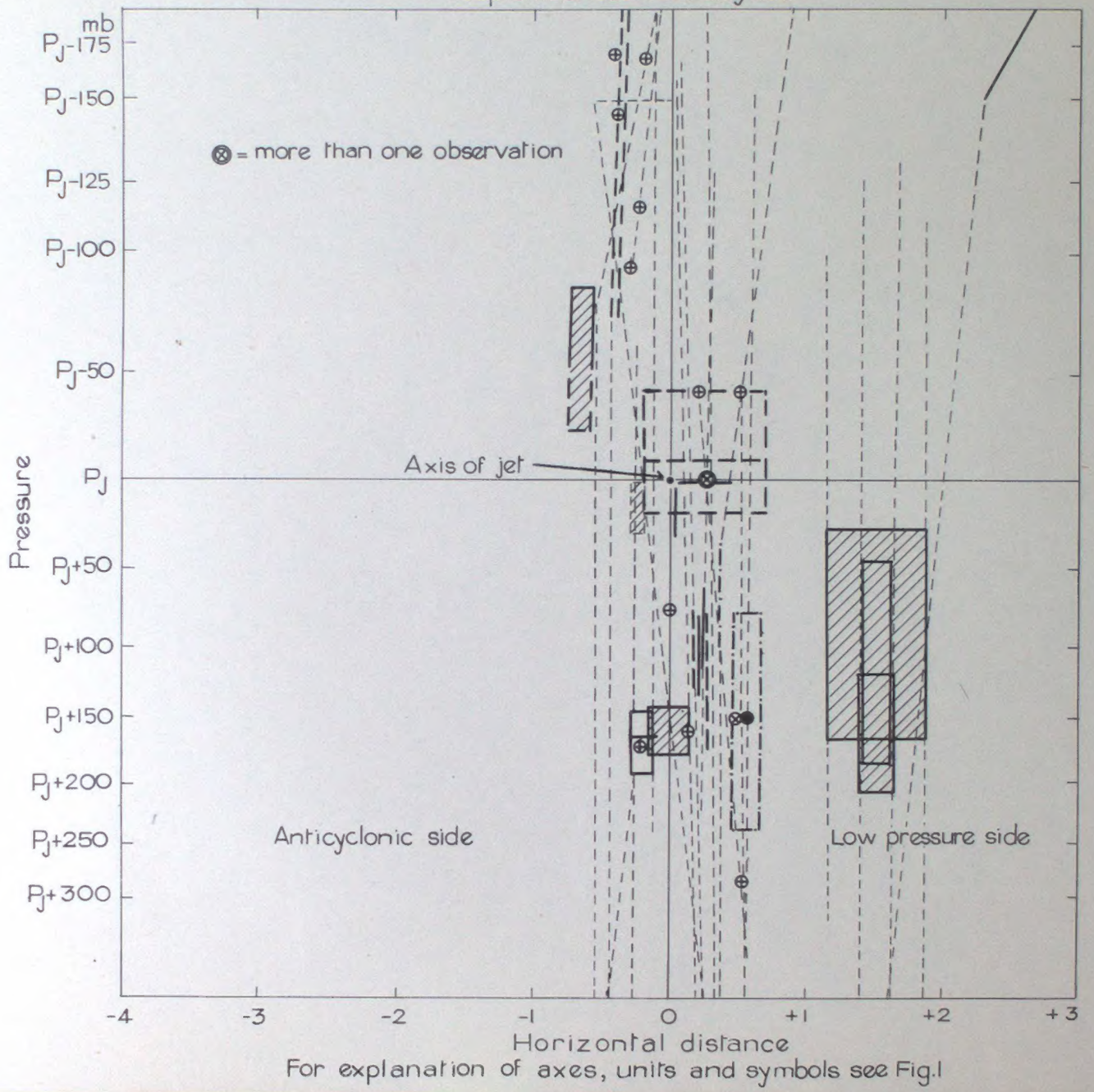
Note:- The unit of horizontal distance is the distance on the low pressure side of the jet axis in which the wind speed is half its maximum value

Fig.2

Positions relative to the axis of jet streams of special flights made by the R.A.F.

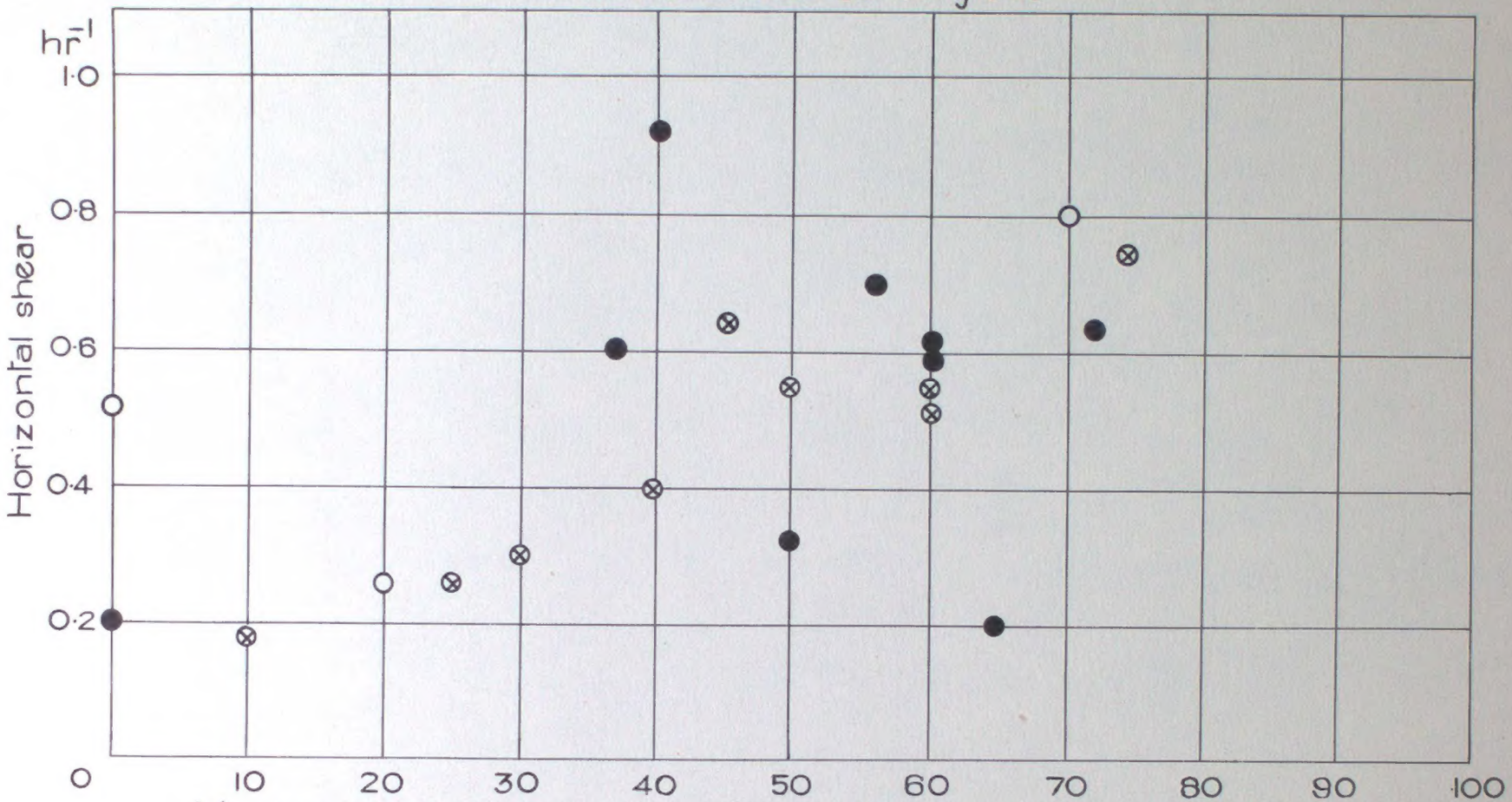
9 jet streams

September 1952 - February 1953



For explanation of axes, units and symbols see Fig.1

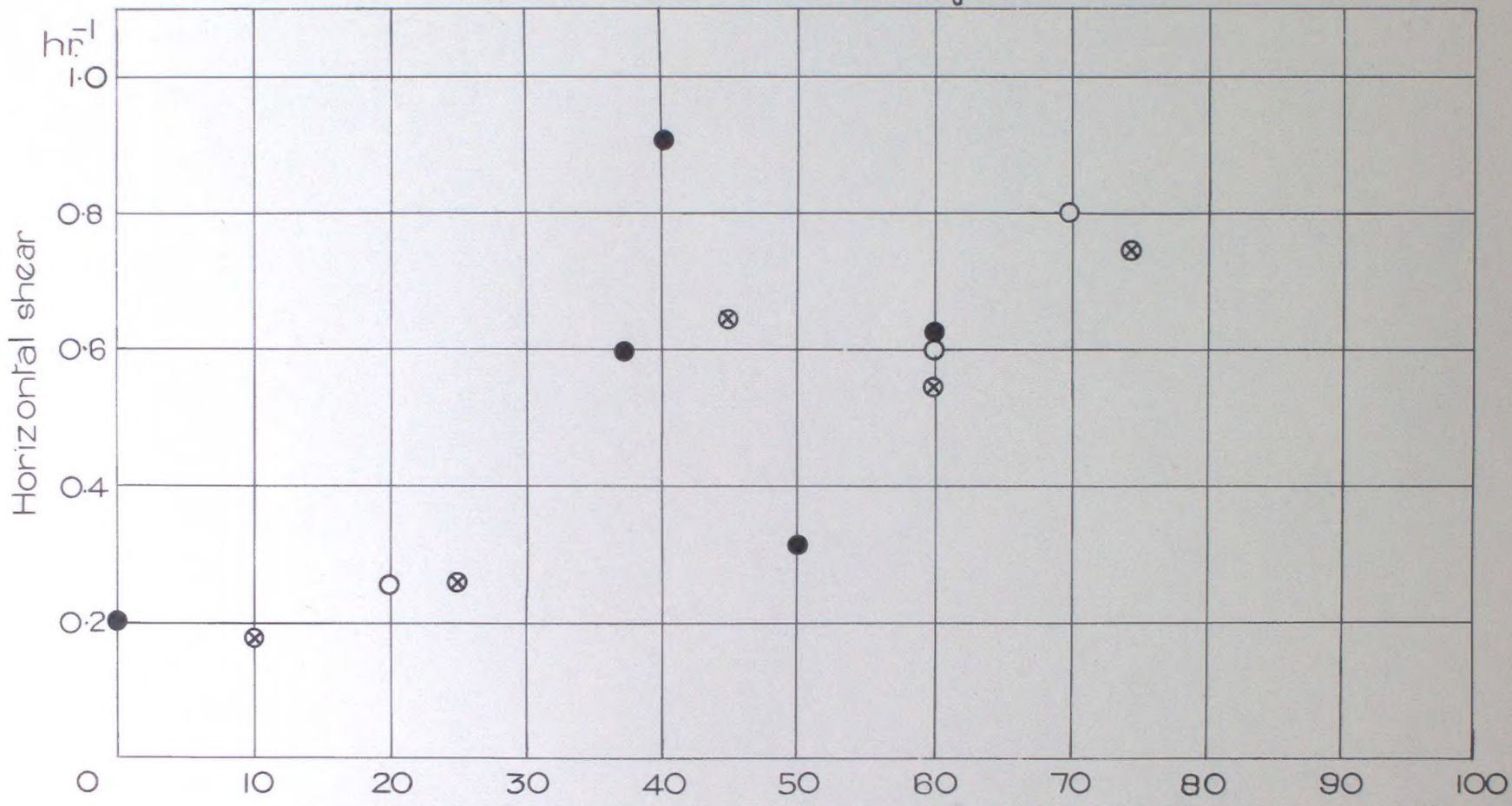
Fig.3
Most severe turbulence encountered in any quadrant of a jet stream
Number of jets investigated-23
R.A.F. March 1952-February 1953



○ Perceptible turbulence
⊗ Moderate turbulence
● Severe turbulence

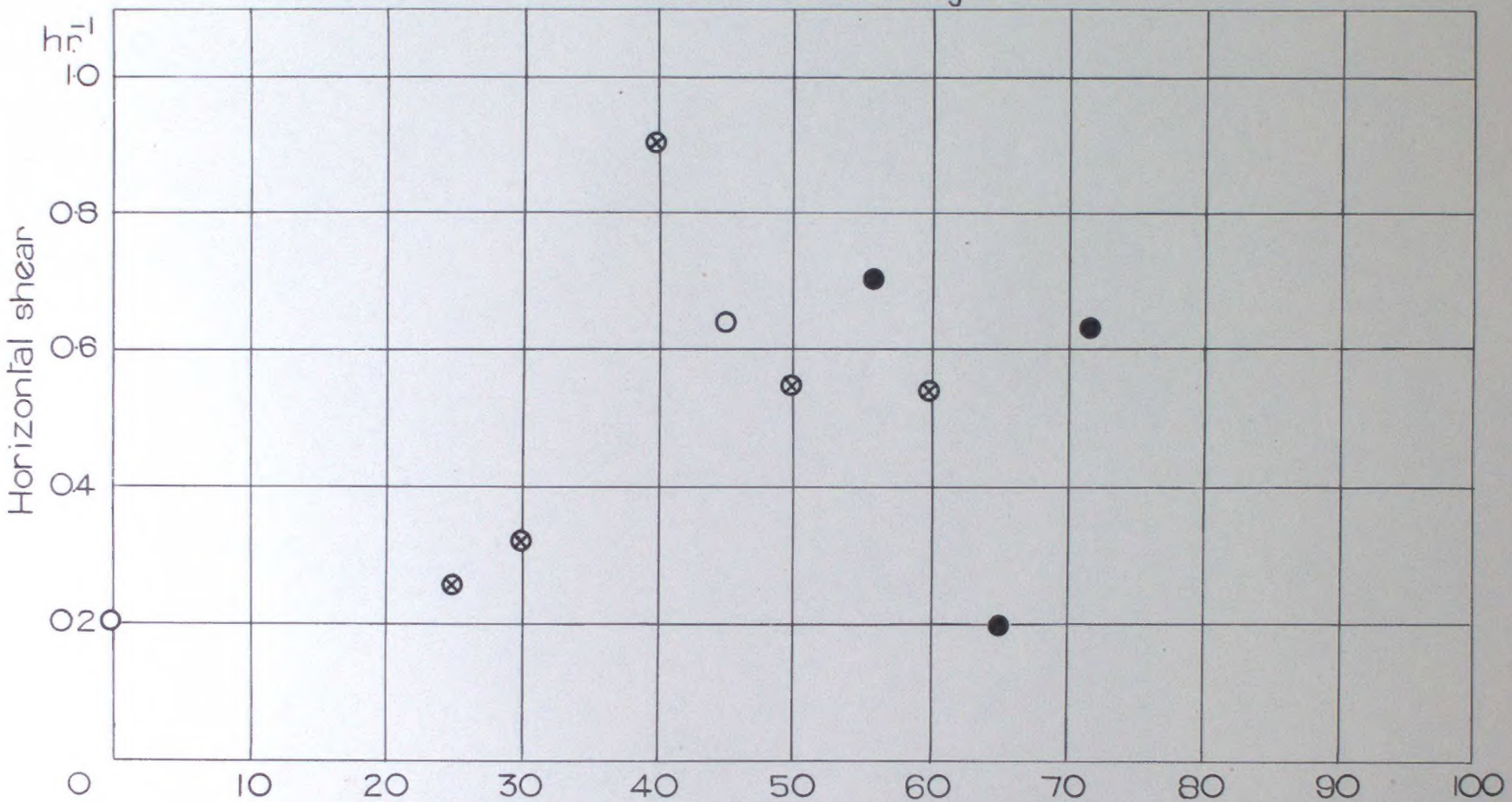
(Nil turbulence encountered on 2 occasions, co-ordinates 30kt. 0·25hr.$^{-1}$; 17kt 0·2hr.$^{-1}$)

Fig.4
Most severe turbulence encountered in the low pressure side below axis of jet
Number of jets investigated=15
RAF. March 1952-February 1953



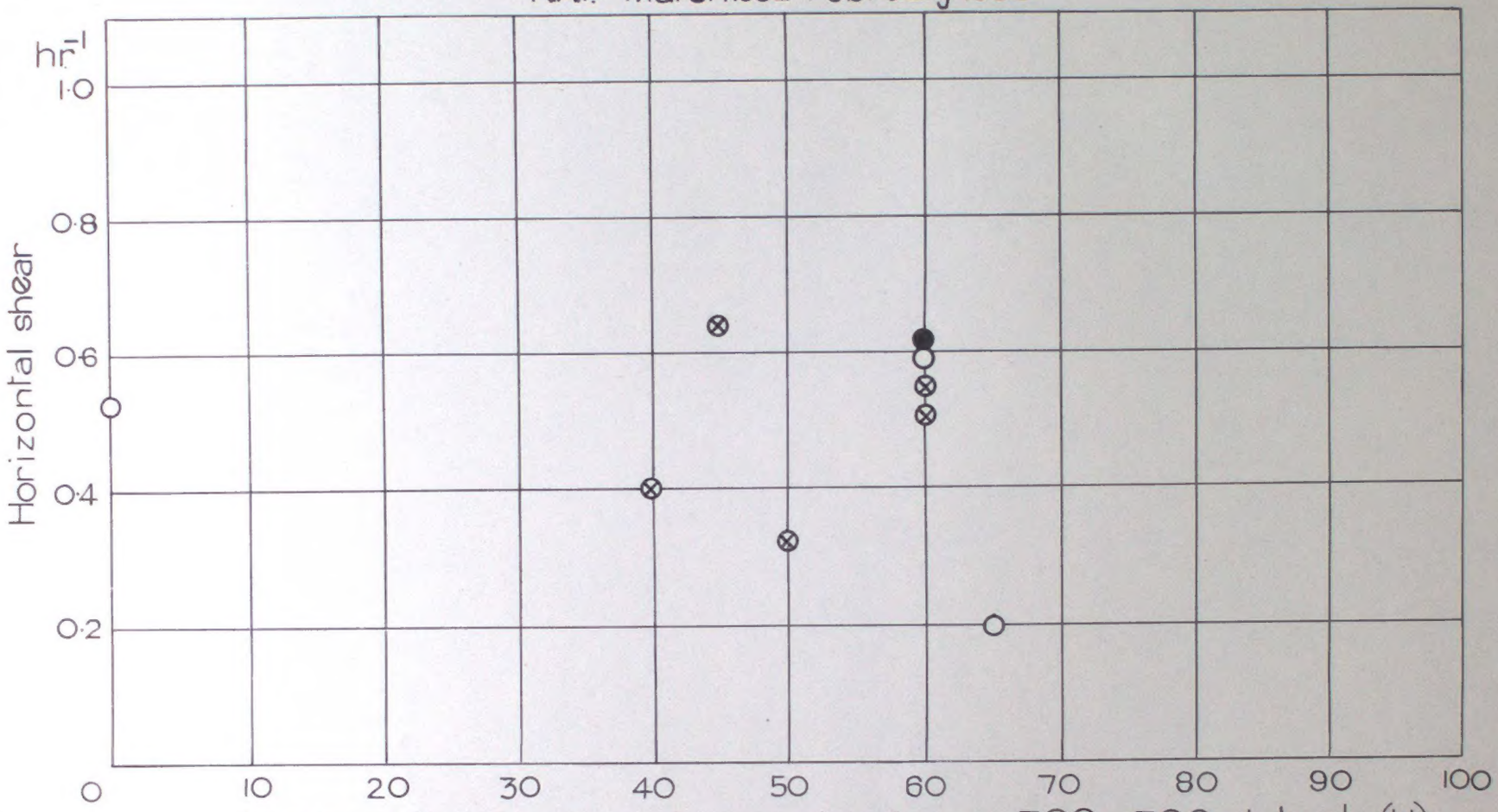
(Nil turbulence encountered on 2 occasions)
For explanation of symbols see Fig.3

Fig. 5
Most severe turbulence encountered in the low pressure side above axis of jet
Number of jets investigated = 13
R.A.F. March 1952–February 1953



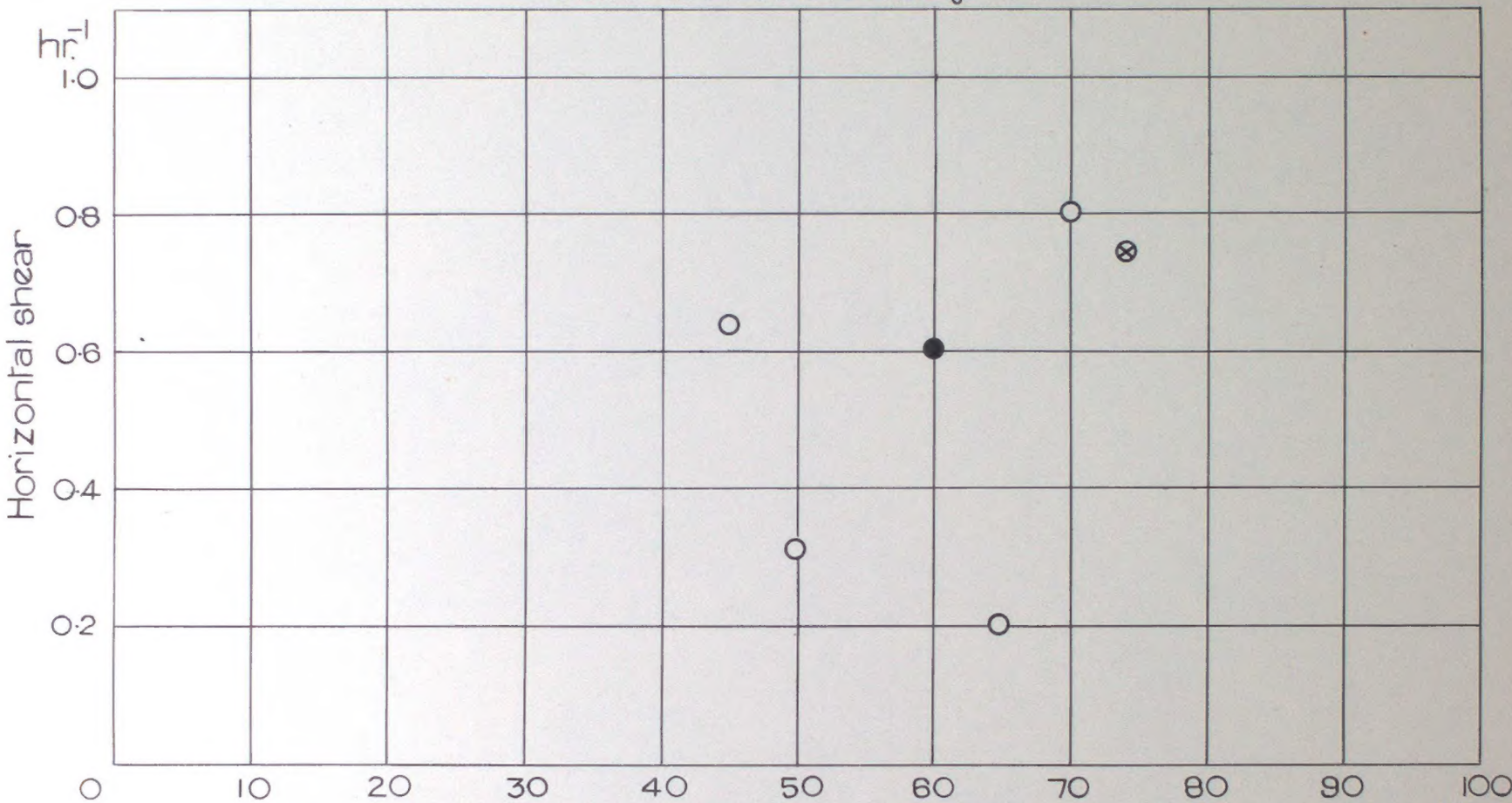
(Nil turbulence encountered on 4 occasions)
For explanation of symbols see Fig. 3

Fig. 6
Most severe turbulence encountered in the high pressure side above axis of jet
Number of jets investigated=12
R.A.F. March 1952-February 1953



(Nil turbulence encountered on 3 occasions)
For explanation of symbols see Fig. 3

Fig.7
Most severe turbulence encountered in the high pressure side below axis of jet
Number of jets investigated=14
R.A.F. March 1952-February 1953

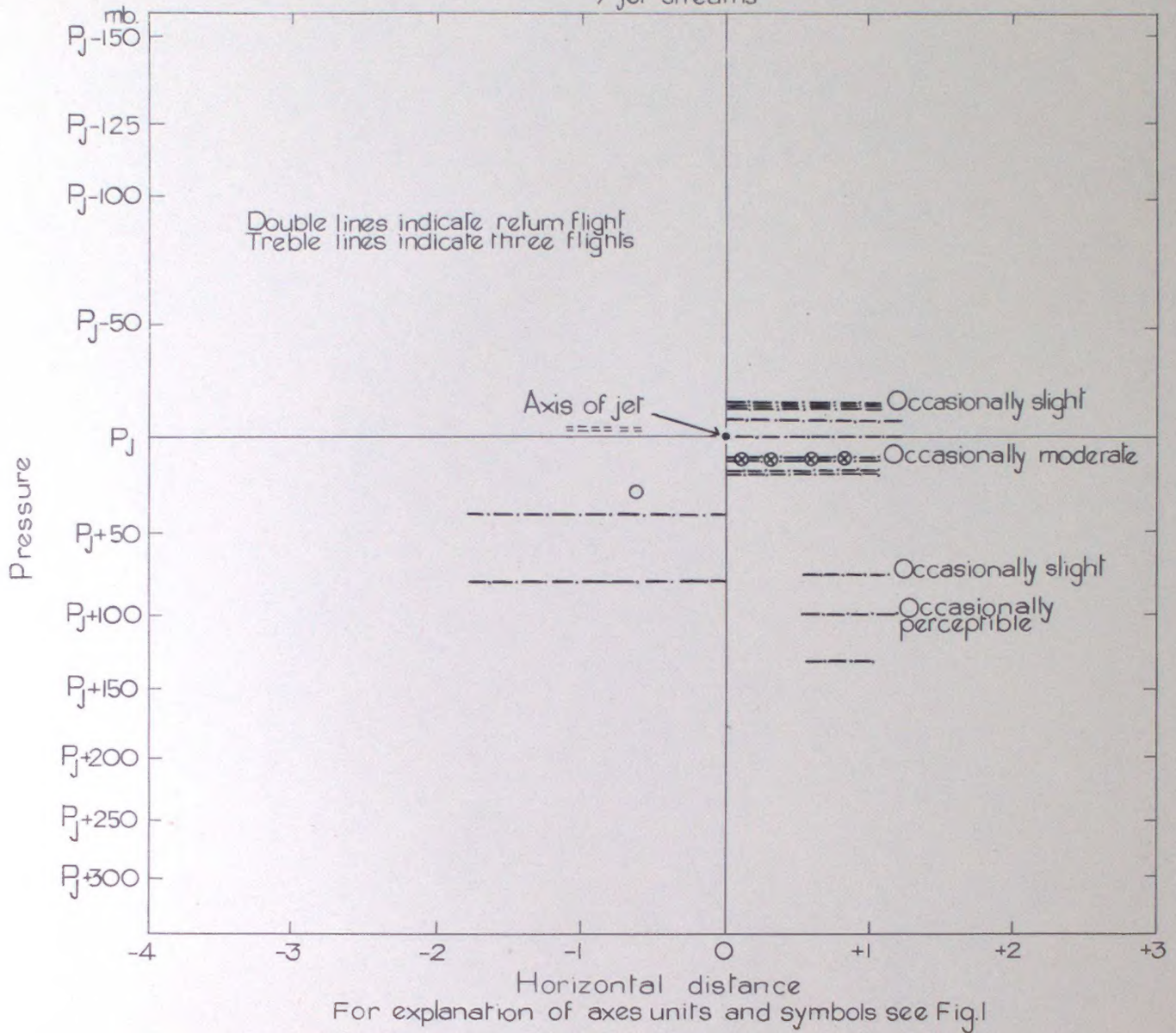


(Nil turbulence encountered on 8 occasions)
For explanation of symbols see Fig.3

Fig. 8

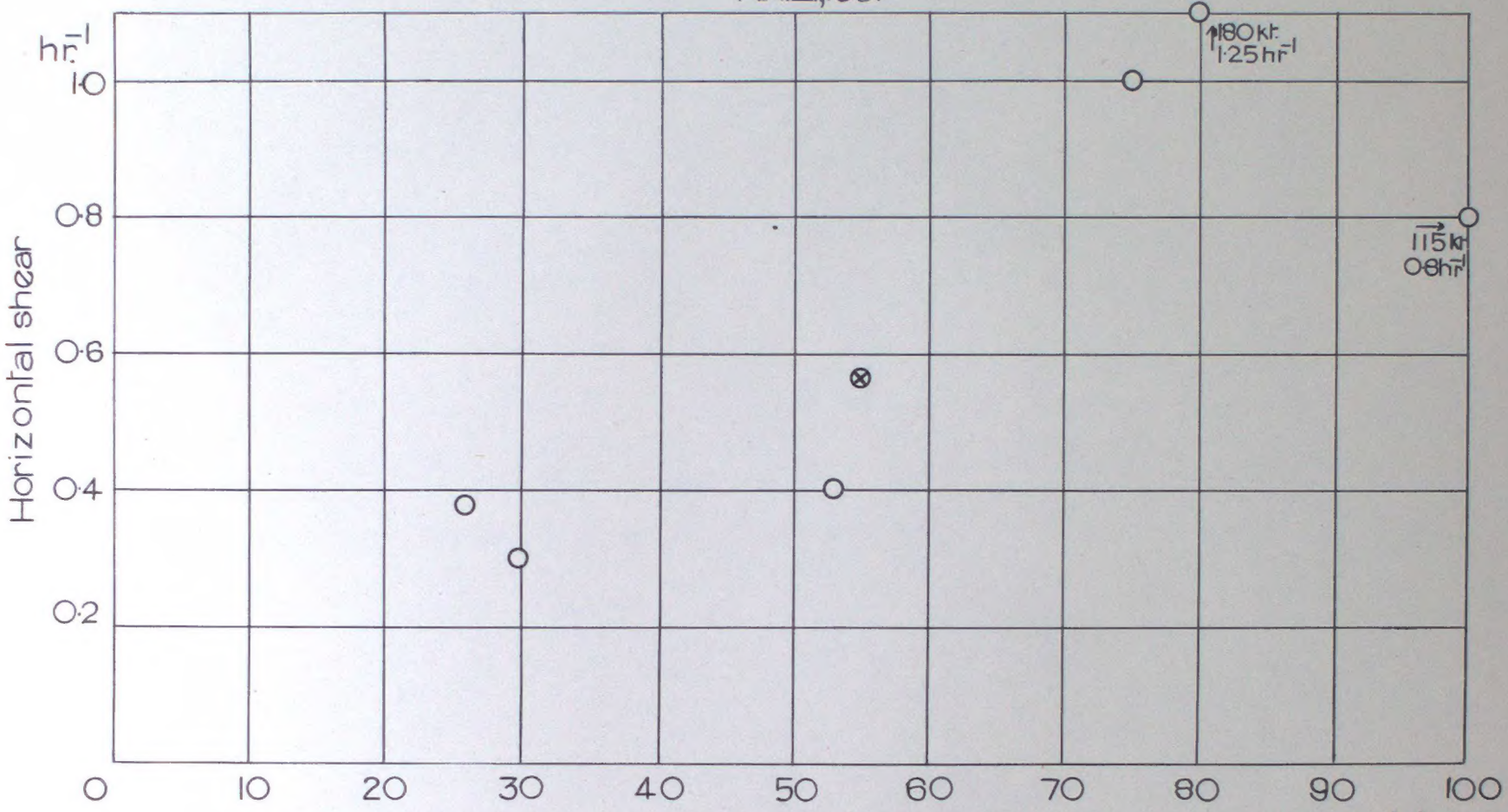
Positions relative to the axis of jet streams of special flights made by Aero. Flight R.A.E.

7 jet streams



For explanation of axes units and symbols see Fig. 1

Fig. 9
Most severe turbulence encountered in any quadrant near a jet stream
Number of jets investigated = 7
R.A.E., 1951



(Nil turbulence encountered on 0 occasions)
For explanation of symbols see Fig. 3